

Spin Asymmetries & \mathcal{P} -Odd Effects through QCD Instantons

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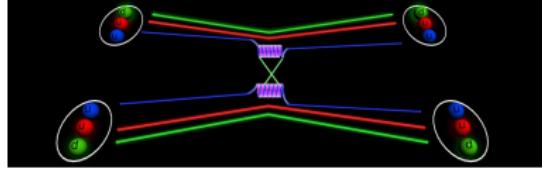
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Outline

- Anomalous Quark Chromomagnetic moment induced by instantons.
- Single Spin Asymmetries induced by instantons in $p_\uparrow p$ collisions.
- Double Spin Asymmetries induced by instantons in $p_\uparrow p_\uparrow$ collisions.
- \mathcal{P} -Odd pion azimuthal charge correlations induced by instantons in heavy ion collisions.
- Summary.



QCD Instantons

Effective Lagrangian[1, 2, 3]

$$\begin{aligned}\mathcal{L} = & \prod_q \left[m_q \rho - 2\pi^2 \rho^3 \bar{q}_R \left(1 + \frac{i}{4} \tau^a \bar{\eta}_{\mu\nu}^a \sigma_{\mu\nu} \right) q_L \right] \\ & \times \exp \left(-\frac{2\pi^2}{g_s} \rho^2 \bar{\eta}_{\gamma\delta}^b G_{\gamma\delta}^b F_g(\rho Q) \right) d_0(\rho) \frac{d\rho}{\rho^5} d\bar{\sigma} + (L \leftrightarrow R) \quad (1)\end{aligned}$$

where the form-factor reads

$$F_g(x) \equiv \frac{4}{x^2} - 2K_2(x) \xrightarrow{x \rightarrow 0} 1 \quad (2)$$

- [2] A. Vainshtein, V. I. Zakharov, V. Novikov, and M. A. Shifman, Sov.Phys.Usp. **25**, 195 (1982).

Effective Vertex [3]

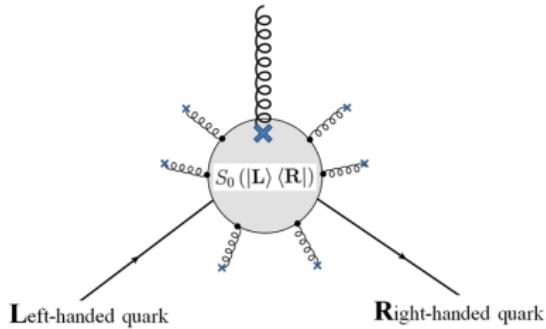


Figure : Effective Quark-Gluon vertex in the instanton vacuum.

- Effective Vertex M_μ^a

$$\gamma_\mu t^a - \frac{2}{g_s^2} F_g(\rho Q) \pi^4 (n_I \rho_c^4) \frac{t^a \sigma_{\mu\nu}}{m_q^*} q^\nu \quad (3)$$

where m_q^* is the effective quark mass.

- Quark Chromomagnetic Moment

$$\mu_a = -\frac{2n_I \pi^4 \rho_c^4}{g_s^2} \approx -0.2 \quad (4)$$

[3] N. I. Kochelev, Phys. Lett. B **426**, 149 (1998)

Single Spin Asymmetries

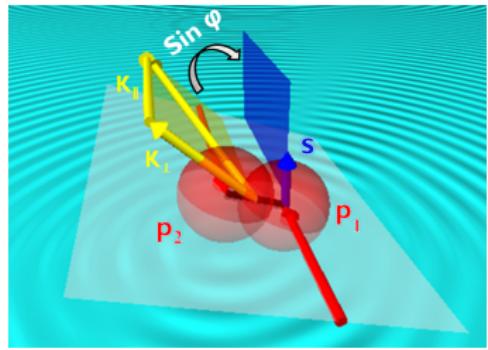


Figure : $p\uparrow p$ collision.

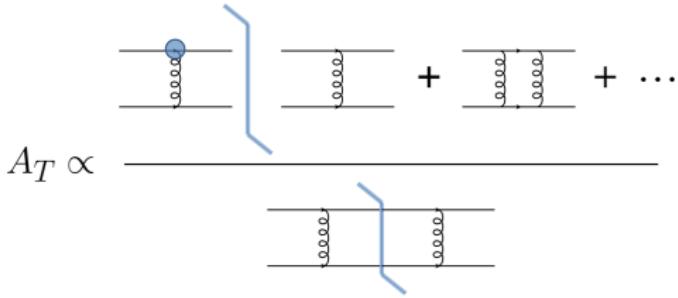


Figure : Schematically diagrammatic contributions to the SSA through effective vertex (Eq. 3) [4].

Definition

$$A_T = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \quad (5)$$

[4] N. Kochelev and N. Korchagin, Phys. Lett. B 729, 117 (2014)

Single Spin Asymmetries

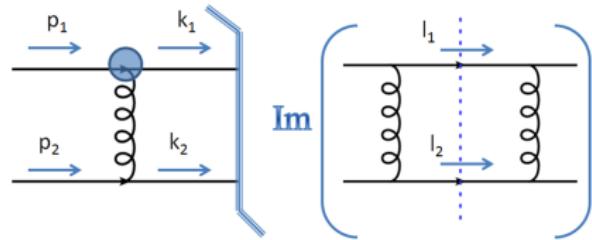


Figure : Diagrammatic contribution to the SSA through the Pauli form factor.

Differential cross section $d^{(1)}\sigma$ for the chirality flip

$$s^\perp k_1^\perp \frac{2g_s^4}{3\pi} \frac{F_g(\rho Q)\pi^4(n_l\rho_c^4)}{m_q^*} \csc^4\left(\frac{\theta}{2}\right)(3 + \cos\theta) \left(-\frac{1}{\epsilon} + 2\gamma_E + \ln\left(\frac{\tilde{s}}{4\pi\mu^2}\right)\right) \quad (6)$$

Single Spin Asymmetries $A_T^{\sin \phi}$ [5, 6]

Gluon Mass m_g Regularized

$$\frac{s^\perp k_1^\perp F_g(\rho_c Q) \pi^3 n_l \rho_c^4 (3 + \cos \theta)}{6m_q^*(5 + 2\cos \theta + \cos^2 \theta)} \left[\ln \left(c \frac{\tilde{s}}{m_g^2} \right) + \ln \left(\frac{1 - \cos \theta}{1 + \cos \theta} \right) \right] \quad (7)$$

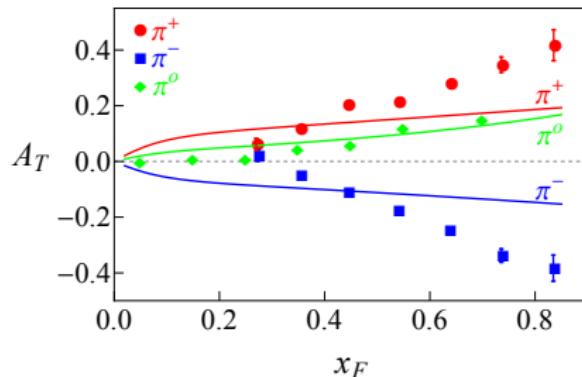


Figure : x_F dependent SSA in $p_1^+ p \rightarrow \pi X$ collisions at $\sqrt{s} = 19.4 \text{ GeV}$ [7] with the instanton vacuum parameters and fixed spin polarized distribution functions [8].

Single Spin Asymmetries $A_T^{\sin \phi}$

Numeric Results

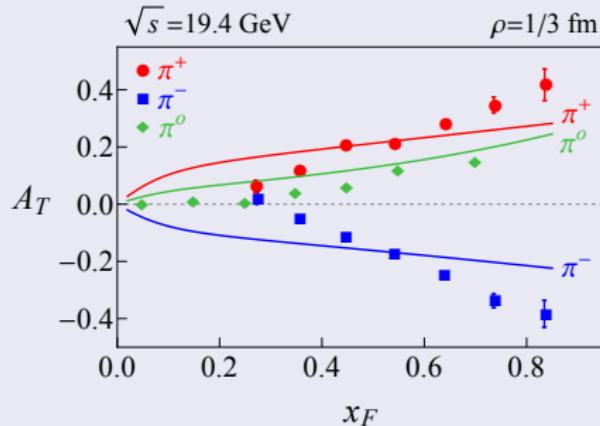


Figure : x_F dependent SSA in $p_{\uparrow}p \rightarrow \pi X$ collisions at $\sqrt{s} = 19.4 \text{ GeV}$ [7] with the instanton vacuum parameters and fixed spin polarized distribution functions [8].

[7] D. L. Adams *et al.* [FNAL-E704 Collaboration], Phys. Lett. B **264**, 462 (1991).

Single Spin Asymmetries $A_T^{\sin \phi}$

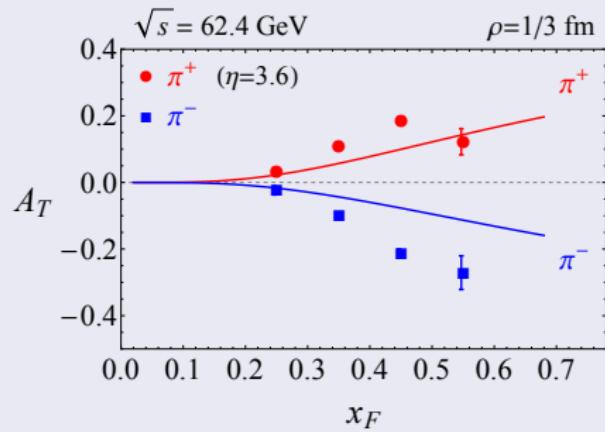


Figure : Data is from [9].

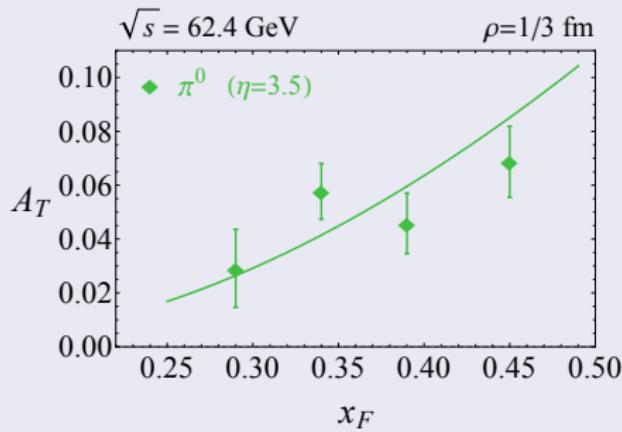


Figure : Data is from [10].

[9] I. Arsene *et al.* [BRAHMS Collaboration], Phys. Rev. Lett. **101**, 042001 (2008)

[10] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. D **90**, 012006 (2014)

Single Spin Asymmetries $A_T^{\sin \phi}$

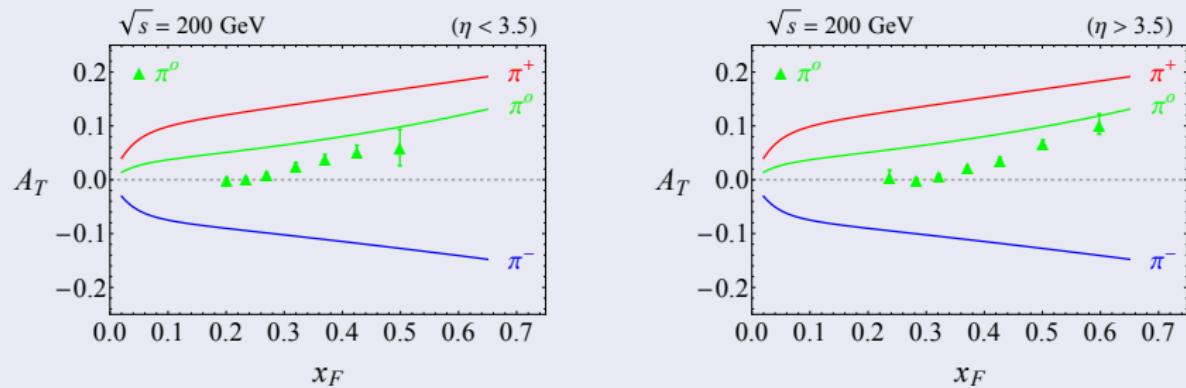


Figure : Data is from [11].

[11] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **101**, 222001 (2008)

Double Spin Asymmetries

Definition

$$A_{DS} = \frac{d\sigma^{\uparrow\uparrow+\downarrow\downarrow} - d\sigma^{\downarrow\uparrow+\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow+\downarrow\downarrow} + d\sigma^{\downarrow\uparrow+\uparrow\downarrow}} \quad (8)$$

$$A_{DS} = \underline{\hspace{8cm}}$$



Double Spin Asymmetries

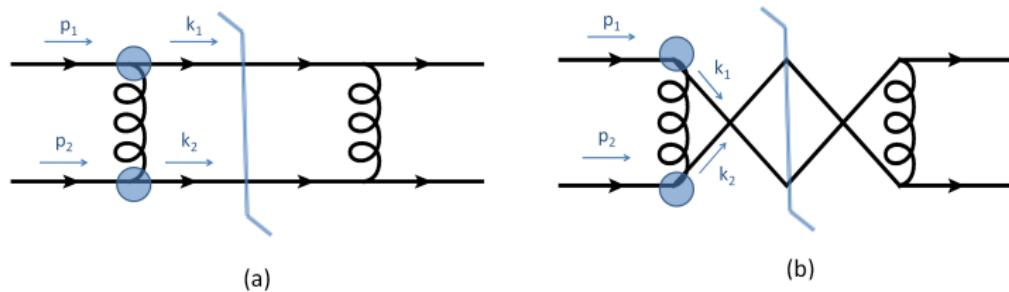
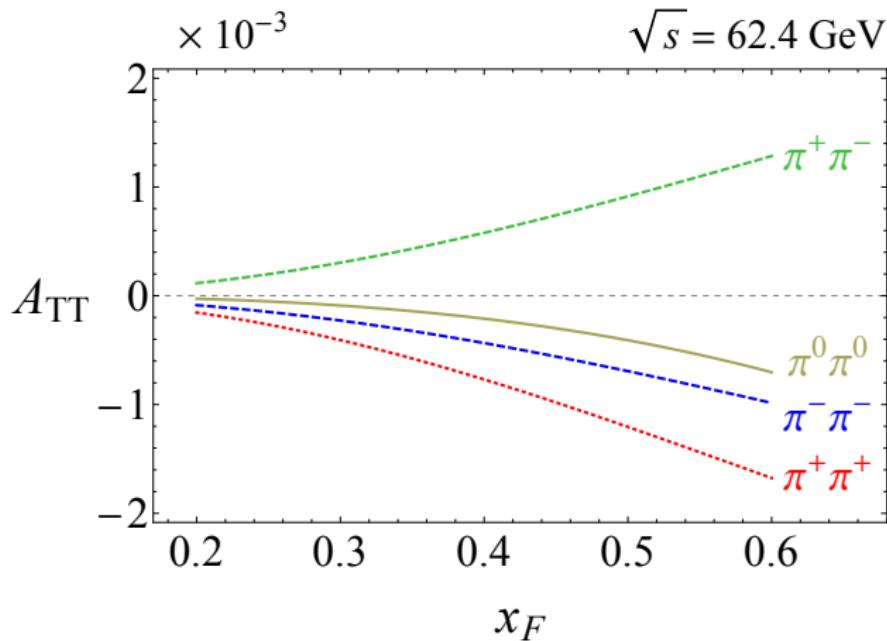


Figure : The valence quark in polarized proton p_1 exchange one gluon with the valence quark in the polarized proton p_2 .

$$A_{TT} \sim -4s_1^\perp s_2^\perp \left(\frac{\pi^4 n_I \rho_c^4}{m_q^* g_s^2} \right)^2 \frac{F_g^2 [\rho_c \sqrt{\frac{\tilde{s}(1-\cos\theta)}{2}}] \tilde{s} + F_g^2 [\rho_c \sqrt{\frac{\tilde{s}(1+\cos\theta)}{2}}] \tilde{s}}{\frac{5+2\cos\theta+\cos^2\theta}{(1-\cos\theta)^2} + \frac{5-2\cos\theta+\cos^2\theta}{(1+\cos\theta)^2}}$$

(9)

Double Spin Asymmetries [6]



[6] Y. Qian and I. Zahed, arXiv:1404.6270

\mathcal{P} -Odd Azimuthal Charge Correlations

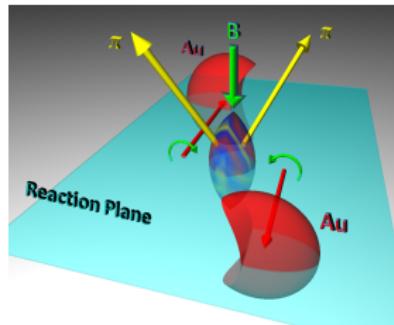


Figure : 2-pion correlations in $AuAu$ after the collision.

After Collision [12, 13, 14, 15]

- ① Heavy-ion collisions may form domains where the parity symmetry in strong interaction is locally violated.
- ② In non-central collisions, these domains may manifest themselves by a separation of charge.
- ③ The existence of the CME, is directly related to the Chiral Symmetry restoration and to large B field values (10^{18} Gauss).

[13] D. Kharzeev, Phys. Lett. B **633**, 260 (2006)

[14] D. E. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A **803**, 227 (2008)

\mathcal{P} -Odd Azimuthal Charge Correlations

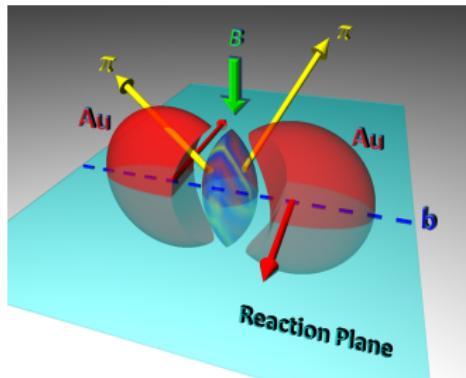


Figure : 2-pion correlations in $AuAu$ at the collision.

During Collision [16]

- ① Incoming nucleus polarizes the participating nucleons from its partner nucleus during the collision.
- ② Topological charges (instantons) cause large pion azimuthal correlations in peripheral heavy ion collisions.
- ③ Topological susceptibility in the interacting instanton liquid.

[16] Y. Qian and I. Zahed, arXiv:1205.2366

\mathcal{P} -Odd Azimuthal Charge Correlations

Effective Vertex

$$M_\mu^a = t^a [\gamma_\mu - \mathbf{P}_+ \gamma_+ \sigma_{\mu\nu} q^\nu \Psi - \mathbf{P}_- \gamma_- \sigma_{\mu\nu} q^\nu \Psi] \quad (10)$$

with $\gamma_\pm = (1 \pm \gamma_5)/2$ and

$$\Psi = F_g(\rho_c Q) \pi^4 (n_I \rho_c^4) / (m_q^* g_s^2) \quad (11)$$

$\mathbf{P}_\pm = 1$ stands for an (anti)instanton insertion.

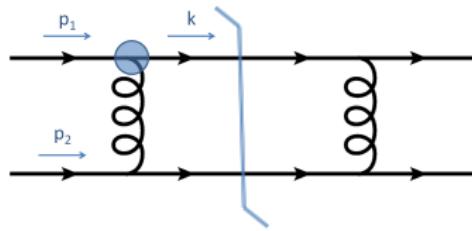


Figure : The blob is an instanton or anti-instanton insertion.

\mathcal{P} -Odd Azimuthal Charge Correlations

Differential Cross Section

$$\frac{d\mathbf{N}}{d\phi_\alpha} \sim 1 - 2a_\alpha \sin(\phi_\alpha - \Psi_{RP}) \quad (12)$$

where

$$a_\alpha = \frac{\Delta_s f(x, Q)}{f(x, Q)} \Upsilon (\mathbf{P}_+ - \mathbf{P}_-) \quad (13)$$

and

$$\Upsilon \equiv \frac{x_F + x}{x_F} \frac{K_\perp}{m_q^*} \frac{\pi^3 (n_l \rho_c^4)}{16 \alpha_s} F_g(\rho Q) \quad (14)$$

\mathcal{P} -Odd

$$\langle a_\alpha \rangle = 0 \quad (15)$$

$$\langle \mathbf{Q} \rangle_V = \langle \mathbf{P}_+ - \mathbf{P}_- \rangle_V = 0 \quad (16)$$

\mathcal{P} -Odd Azimuthal Charge Correlations

Measurements

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \equiv -\langle a_\alpha a_\beta \rangle \quad (17)$$

Topological susceptibility [17]

$$\begin{aligned} \langle \mathbf{Q}^2 \rangle_V &= \langle (\mathbf{P}_+ - \mathbf{P}_-)(\mathbf{P}'_+ - \mathbf{P}'_-) \rangle_V = \left\langle \left(\frac{N_+ - N_-}{N_+ + N_-} \right)^2 \right\rangle_V \\ &\approx \frac{\left\langle (N_+ - N_-)^2 \right\rangle_V}{\left\langle (N_+ + N_-)^2 \right\rangle_V} = \frac{\langle N \rangle_V}{\langle N \rangle_V (\langle N \rangle_V + 4/\mathbf{b})} \end{aligned} \quad (18)$$

where

$$\mathbf{b} = 11N_c/3 \quad (19)$$

[17] D. Diakonov and V. Y. Petrov, Nucl. Phys. B **245**, 259 (1984)

\mathcal{P} -Odd Azimuthal Charge Correlations [16]

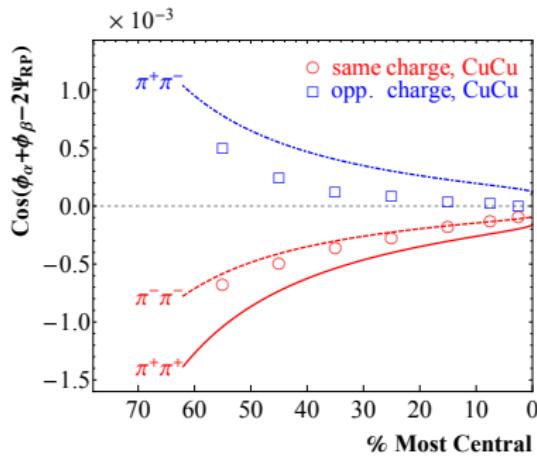
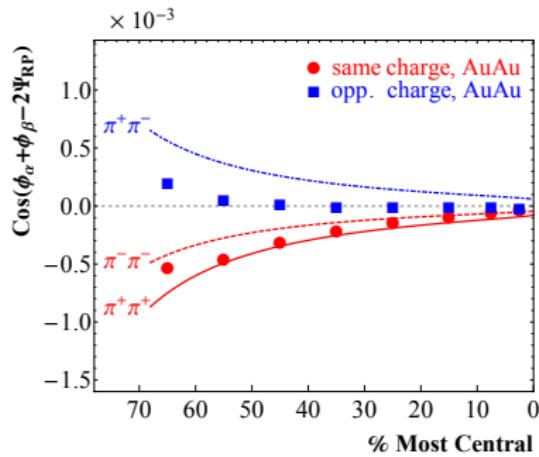


Figure : Pion azimuthal charge correlations versus the data [18] from STAR at $\sqrt{s} = 200\text{GeV}$ with the instanton vacuum parameters and fixed spin polarized distribution functions [8].

[18] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **103**, 251601 (2009)

\mathcal{P} -Odd Azimuthal Charge Correlations [16]

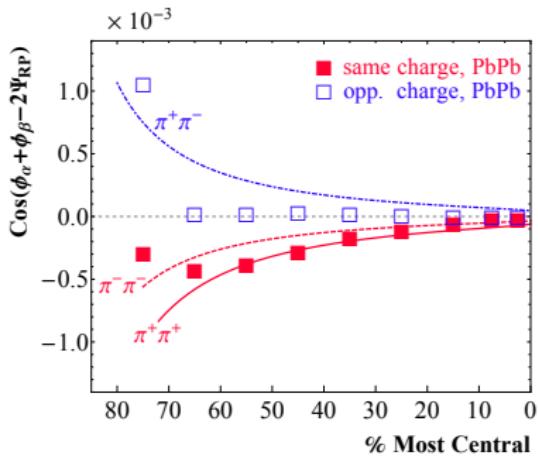


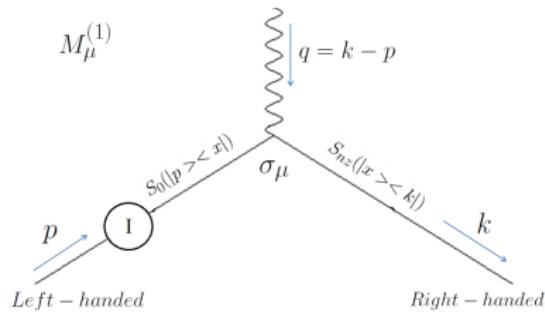
Figure : Pion azimuthal charge correlations versus the data from ALICE [19] at $\sqrt{s} = 2.76\text{TeV}$ with the instanton vacuum parameters and fixed spin polarized distribution functions [8].

[19] I. Selyuzhenkov [ALICE Collaboration], PoS WPCF 2011, 044 (2011)

*Ongoing Project

Single spin azimuthal asymmetry [5, 20]

$$e^- + p_{\perp} \longrightarrow e^- + \pi + X \quad (20)$$



Extract

Parton's helicity distribution in a proton!

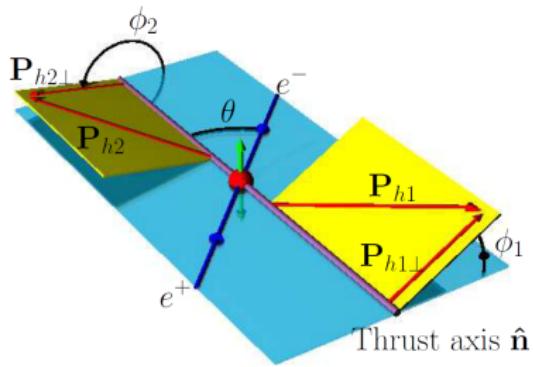
[5] Y. Qian and I. Zahed, Phys. Rev. D **86**, 014033 (2012) [Erratum-ibid. D **86**, 059902 (2012)]

[20] D. Ostrovsky and E. Shuryak, Phys. Rev. D **71**, 014037 (2005)

*Ongoing Project

Azimuthal asymmetry [21]

$$e^+ + e^- \longrightarrow h_1 + h_2 + X \quad (21)$$



Extract

Parton's transversity distribution in a proton!

[21] K. Abe *et al.* [Belle Collaboration], Phys. Rev. Lett. **96**, 232002 (2006)

*Ongoing Project

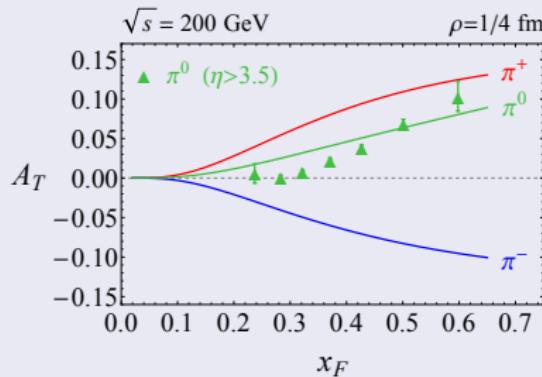
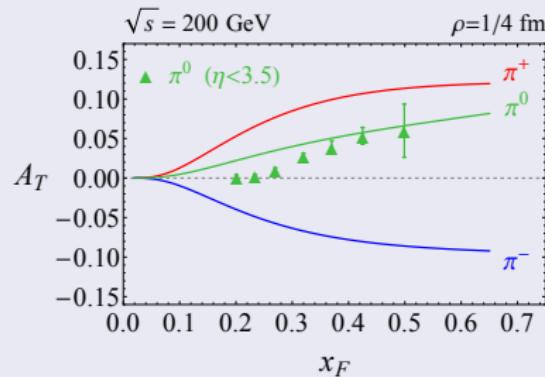


Figure : Data is from [11].

Summary

- QCD instantons provide a natural mechanism for large Single Spin Asymmetries in polarized hadron scattering.
- QCD instantons yield substantial Double Spin Asymmetries in polarized hadron scattering.
- QCD instantons contribute substantially to \mathcal{P} -odd azimuthal correlations in *unpolarized* AA collisions at RHIC and LHC.

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Thank You!

